Physics of Magnetic Storms

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Abstract: Magnetic storms are defined by the presence of a ring current which comes into existence through the acceleration of particles during episodes of strongly enhanced input of energy from the solar wind into the magnetosphere. The main phase of a storm, during which the primary ring current growth takes place is typically accompanied by sustained substorm expansive phase activity, leading to the suggestion that substorm perturbations play a role in ring current growth. In this paper we shall show that substorm expansive phases do indeed play an important role in energization of ring current particles; however they contribute only a small portion of the energy which is typical for ring current particles. It appears that the dynamical changes in the near-Earth tail magnetic field which occur during substorm expansive phases are not effective in ring current generation regardless of the proximity of the locale of the initiation of the expansive phase with respect to the Earth. Rather, the substorm expansive phase involves a breakdown of the shielding electric field and, in this way, substorms cause the locale of future expansive phases to migrate further earthward. This, in turn, permits plasma sheet ions to penetrate closer to the Earth and become energized adiabatically to the rather high energies typical of the particles that contribute significantly to the ring current. Cyclical stretching and dipolarization of the near-Earth tail magnetic field can energize plasma sheet ions to the extent that the incremental energy provided by the convection electric field may lead to energies in excess of 100 keV for ring current particles and enhance the lifetime of the ring current itself.

1. INTRODUCTION

Of all magnetic perturbations of the Earth's main field, the one that has been known the longest and studied most intensively in the pre-satellite era has been the magnetic storm. In its classic form (Figure 1), it is manifested by a sudden increase in the north-south (H) component of the low latitude magnetic field (the ssc), followed some time later by a depression in that component developing over a time span of one to a few hours and concluding with a decay which may extend over several days. The size of the ssc ranges from a few nT to over 100 nT while the main phase of storms may reach strengths of a few hundred nT. The ssc is understood to be a consequence of enhanced solar wind dynamic pressure, and in modern times, is not considered to be a necessary component of the storm (cf. Akasofu, 1965). Thus the storm is defined purely by the growth and subsequent decay of the depression in the H-component of the low latitude magnetic field.

The strength of magnetic storm is usually measured by the magnitude of the Dst index. This index, introduced by *Sugiura* [1964] for the study of IGY data, was developed as a measure of the symmetric component of the ring current. The H-component of the surface magnetic field at low latitudes is measured at several stations distributed in longitude. After subtraction of the quiet time baseline (removing the effects of

Magnetic Storms
Geophysical Monograph 98

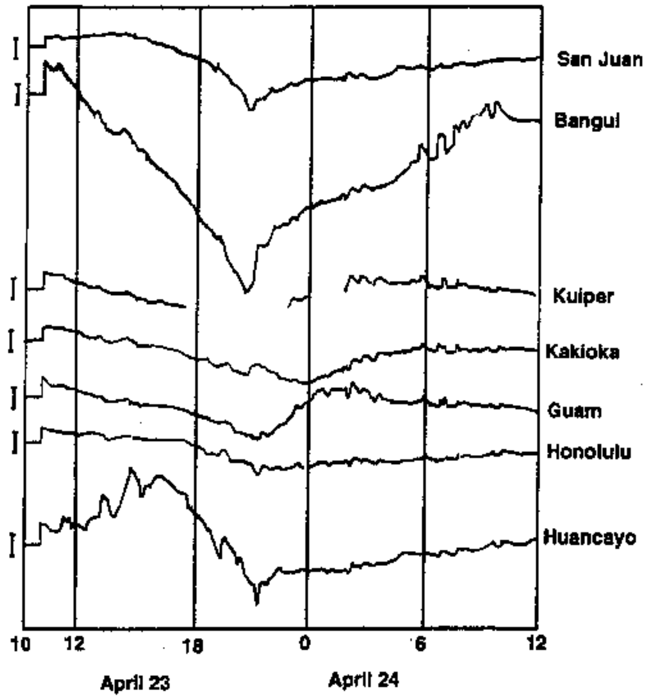

Fig. 1. Low latitude H-component magnetograms taken during the course of a magnetic storm on April 23-24, 1959, at a number of stations located at different longitudes. The vertical bars on the left side of the figure indicate 50 nT. There is evidently a large long lived negative H-component perturbation at all stations, however there is clearly a local time variation in in the character of the disturbance field. The Dst index is an attempt to identify the component of the disturbance field which is not dependent on local time.

Sq), the average value of the H-components of the contributing stations is calculated and multiplied by the secant of the average latitude of the contributing stations to define Dst (cf. Rostoker, 1972). Ideally, the index does not contain contributions from current systems which are not azimuthally symmetrical. Unfortunately, the fact that data from very few (viz. as little as four) stations are used in the computation of the index permits contributions from other current systems to leak into the index (viz. the asymmetric ring current, the magnetotail current as well as contributions to the H-component from field-aligned currents). Thus every value of Dst may be thought of as the value due to the symmetric ring current together with some "error" associated with the contributions of other current systems. We shall provide a measure of the size of the expected "error" later in this paper.

When researchers study magnetic storms, they typically choose events for which the main phase features a Dst of tens to hundreds of nT. Curiously, there is no well defined limit for the lower limit of Dst for which one can say a storm does or does not exist. There are operational definitions for the purposes of predictions, with ~50 nT being the lower limit [*Joselyn and Tsurutani*, 1990]. However, there is no physical reason why any particular magnitude of Dst should be chosen as a lower limit. Thus, when one says that a particular group of substorms is or is not associated with an episode of ring current growth, no study has yet been performed to establish that fact based on a quantitative measure which establishes the presence or absence of a storm time ring current. Later in this presentation, we shall try to look at this question of what kind of lower limit can be set above which the presence of a storm time ring current can be established.

We should now like to address the question of what constitutes a magnetospheric substorm, so that we can better understand how the development of a storm time ring current might be related to substorms in general. It is now reasonably well accepted that a substorm involves two distinctive processes.

The first of these is the directly driven process in which energy from the solar wind that enters the magnetosphere is immediately deposited in the high latitude ionosphere with the only delay being the Alfvén propagation time from the magnetospheric boundary layers to the ionosphere (cf. Akasofu, 1979; Rostoker et al., 1987). The electric current manifestations of the directly driven process are the eastward and westward electrojets flowing from near noon across the dusk and dawn meridians, respectively (Figure 2a). These primarily Hall currents flow in the auroral oval and are colocated in the ionosphere with the Birkeland currents (cf. Zmuda and Armstrong, 1974) which flow into and out of the auroral ionosphere in anti-parallel sheets linked by primarily Pedersen meridonal ionospheric currents. The Region 1 and Region 2 Birkeland currents (cf. Iijima and Potemra, 1976) are offset such that there is net downward field aligned current across the noon sector and net upward field-aligned current across the the midnight sector. These large scale currents vary rather slowly, but are responsible for the dissipation of a considerable amount of the energy which enters the magnetosphere from the solar wind.

The second of the the substorm processes is the storage/release process in which some of the energy from the solar wind is stored in the magnetotail as the magnetic energy of the tail lobe and as the drift energy of the earthward convecting plasma in the tail plasma sheet. From time to time, this energy is released in what is termed expansive phase activity. (It is extremely important to note here that most researchers, when they use the term substorm, are actually referring to the expansive phase of the substorm. In this paper we shall try to be explicit in referring to the phenomenon accompanying the auroral breakup (cf. Akasofu, 1964) as the expansive phase.) It is, in fact, a major problem for the substorm researcher to distinguish between directly driven activity and substorm expansive phase activity using magnetometer data since both involve changes in westward electrojet strengths.) Expansive phases are often triggered by decreases in energy input from the solar wind to the magnetosphere, commonly induced by a weakening of a southward IMF or a turning towards the north of the IMF (cf. Caan et al., 1977; Rostoker, 1983). The storage process normally occurs concurrent with growth of the directly driven current systems after the start of increased

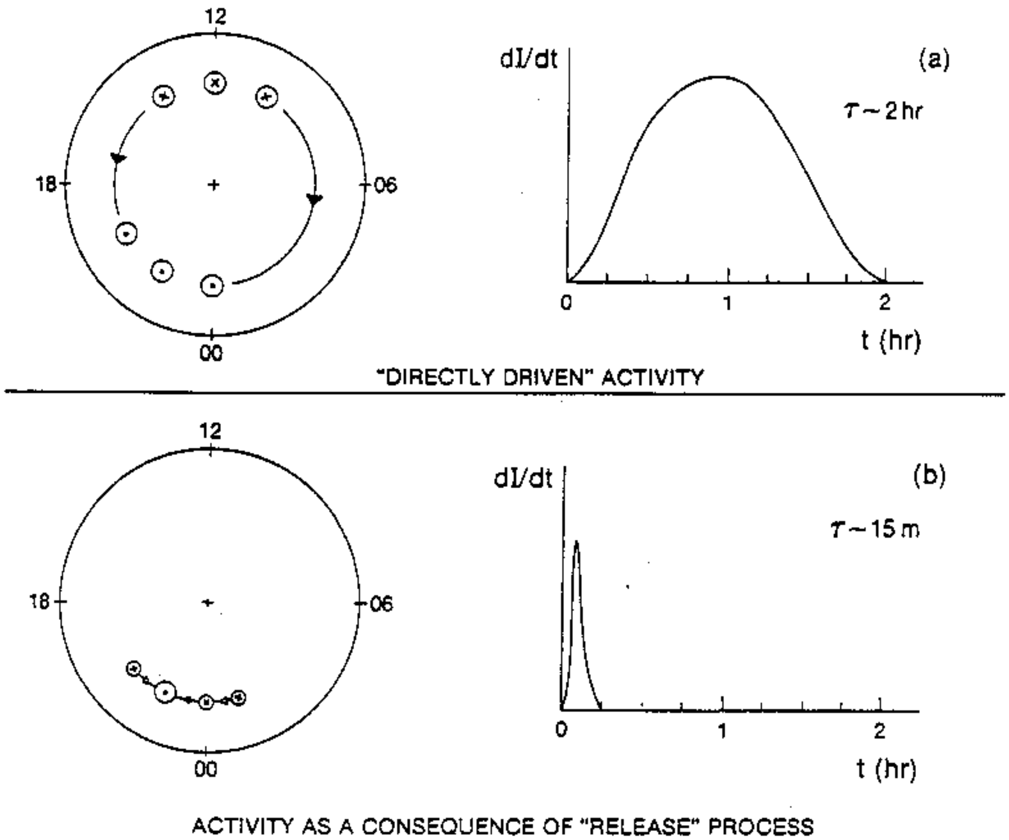

Fig. 2. Cartoon showing the two components of substorm activity. Fig. 2a shows the large scale eastward and westward electrojets associated with directly driven activity while 2b shows the localized field-aligned and ionospheric currents associated with an expansive phase intensification (after Rostoker, 1991). A substorm expansive phase involves the development of many small localized current elements such as that shown in 2b, and the ensemble of these structures contributes significantly to the overall substorm magnetic perturbation pattern.

energy input into the magnetosphere (typically as the result of a southward turning of the IMF). The expansive phase involves the sudden growth of an azimuthally confined segment of westward electrojet in the late evening sector, beginning near the equatorward edge of the auroral oval [*Samson et al.*, 1992]. As expansive phase activity develops after onset, the activity spreads poleward in discrete steps [*Kisabeth and Rostoker*, 1974]. After the maximum poleward movement has taken place, activity may continue for some time afterwards both at the poleward edge of the expanded oval and near its equatorward border. When the substorm moves into its recovery phase, the activity is normally restricted to the poleward border of the oval. However, the magnetic disturbances at the poleward border can be quite strong although the substorm might be said to be in its recovery phase (cf. Lyons et al., 1990).

2. CONCEPTS OF HOW SUBSTORMS MIGHT INFLUENCE THE GROWTH OF THE STORM TIME RING CURRENT

The question of how substorms relate to the development of a magnetic storm has long been a subject of intense discussion. *Kamide* [1979] has explored the suggestion by *Akasofu* [1968] that a magnetic storm simply was the sum of polar magnetic substorms together with the ring current (which is the unique feature of storm). In fact, *Kamide* [1992] specifically explored the question of whether or not a substorm is a necessary component of a magnetic storm. In light of the fact that the symmetric ring current signature (quantified by the index Dst) appears to be the unique identifier of a magnetic storm, we shall devote this paper to an effort to understand the nature of the physical processes through which the ring current is created.

A storm involves the energization of a radially localized population of protons to energies in excess of ~100keV in an L-shell range which is earthward of the typical position of the inner edge of the plasma sheet. During the development of the main phase, significant amounts of oxygen are transported out of the ionosphere into the near-Earth plasma sheet (cf. Lennartsson and Shelley, 1986). The distinguishing feature of the stormtime ring current is the length of time required for its decay compared to normal decay times of substorm related currents. As mentioned earlier (cf. Figure 2a), the large scale electrojets vary on a time scale of many tens of minutes. In fact, *Rostoker et al.* [1991] have shown that for sudden northward turnings of the IMF followed by extended periods of northward IMF, the decay times of the auroral electrojets is of the order of an hour. The wedgelets which characterize the intensifications taking place during the expansive phase tend to have decay time of the order of ~15 min (cf. Figure 2b). In contrast, the ring current decay times range from a few hours (associated with its energetic oxygen component) to several tens of hours (associated with its energetic proton component).

In trying to understand how ring current particles might be energized to the levels of ~100-200 keV which have been identified as the most important in terms of the ion population identified as the current carriers, one is initially tempted to look to the rapid time variations of the magnetic field associated with substorm expansive phase activity. This first approach seems natural since *Akasofu and Chapman* [1961] have identified auroral oval substorm expansive phase activity as a unique feature of the period of time in which ring current growth takes place. However, one quickly realizes that there are many substorm expansive phases which seem to have no particular response in terms of ring current growth. This could mean one of two things. On one hand, it may suggest that the expansive phases *per se* have no major impact in terms of energizing ring current particles. This would be consistent with the suggestion by *Burton et al.* [1975] that the energization is simply a consequence of the convection electric field moving plasma sheet particles closer to the earth. For such a scenario, the energization would be adiabatic reflecting the combined effects of betratron and Fermi acceleration (cf. Hines, 1963). Another possibility is that substorm expansive phases which are triggered too far from the Earth cause acceleration of particles which are unable to make complete drift paths around the Earth and hence cannot form a long lived symmetric ring current. Only if the expansive phases are triggered relatively close to the Earth (viz. the inner edge of the tail current has moved sufficiently earthward) will the energized particles be able to make complete circuits around the Earth and hence form a symmetric ring current. This has been suggested by *Rostoker* [1994a, 1996a] and we shall explore the latter possibility in this paper.

3. RESPONSE OF THE RING CURRENT INDEX DST TO EQUATORWARD MOVEMENT OF THE OVAL

Substorm magnetic field variations with magnitudes of tens of nT are often observed at latitudes many hundreds of kilometers equatorward of the equatorward edge of the auroral oval. Typically, the perturbations are in the horizontal (H and D) components and are due to the distant effect of field-aligned currents associated with the substorm current wedge, the directly driven system or with both. Detection of such perturbations at middle latitude stations gives no indication of the proximity of the auroral electrojets. However, as can be seen from Figure 3 the equatorward edge of the auroral electrojets and regions immediately equatorward of that boundary is marked by a significant Z-component perturbation (positive equatorward of an eastward electrojet and negative equatorward of a westward electrojet). The presence of a Z-component perturbation at a middle latitude station should be a sure sign of the proximity of an auroral electrojet and we shall use it as our proxy for the location of the auroral electrojets. One might think that it would be better to use the total perturbation magnetic field, as for situations in which an electrojet has its center directly above an observing station, no Z-component perturbation would be detected. However, as mentioned earlier substorm current wedges have field-aligned currents which produce significant magnetic perturbations in the horizontal plane despite the fact that the ionospheric wedge currents may be far distant from the observing site. This, we believe, is more of a source of error than having an electrojet accidentally stay with its center over a given observing site. Hence we used purely the Z-component perturbation as our proxy for the proximity of the auroral electrojets. In our study we used data from three years (1989, 1990 and 1991) from the three low latitude stations of Fredericksburg, Boulder and Fresno and the middle latitude station of Newport about 500 km north of Fresno. Most of the work involved the use of the low latitude stations, excluding Newport, which was treated separately.

The two parameters we shall be correlating are Dst (as a proxy for the strength of the symmetric component of the ring current) and the perturbation in the Z-component of the magnetic field dZ (as a measure of the proximity and strength of the auroral electrojets). Both of these parameters are imperfect measures of what they purport to show, however it is possible to correct them to make them somewhat more acceptable. In the case of Dst, there are three potential problems:

1. Since there are nowadays only four stations at most used for the computation of Dst, it is not possible to obtain a measure of the symmetric ring current without some contamination from the asymmetric ring current associated with substorm activity. Thus, there is always some "noise level" associated with contributions from non-ring current systems.

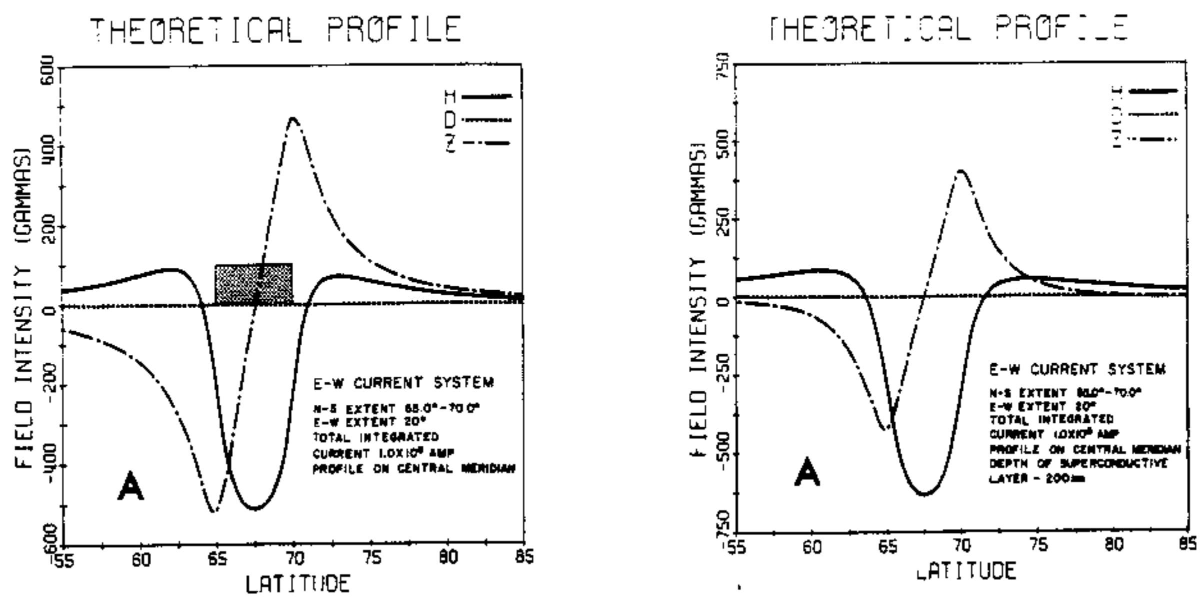

Fig. 3. Model latitude profiles from a current wedge involving a westward electrojet (after Kisabeth, 1972). The left hand panel shows the magnetic perturbations due to the current system not including effects of induced currents in the ground. The right hand panel shows the magnetic perturbations for the same source current system but including the effects of induced currents where the Earth is simulated by a superconductor starting 200 km below the surface. From profiles such as these one can establish the positions of the borders of the electrojet (which is uniformly distributed over 5 degrees of latitude between 65-70 degrees in this figure) and establish correction factors taking induction into account at each latitude.

2. Earth induction effects are not subtracted from the observed magnetic field perturbations before they are merged to compute the Dst index. Thus the magnitudes given for Dst contain an induction contribution and do not reflect the strength of the source (ring) current distribution alone.

3. Changes in solar wind dynamic pressure change the value of Dst.

For the first two problem areas, there is little that can be done at the present time. Fortunately, the second problem area identified does not have a severe impact except in cases where one of the Dst stations is sited near a subsurface conductivity anomaly. (This is the case for Honolulu, and should be a matter of concern for any researcher who looks for diurnal trends in Dst.) It is possible, however, to correct for solar wind dynamic effects using a relationship suggested by *Burton et al.* [1975] and developed further by *Gonzalez et al.* [1989], viz.

$$Dst_{corr} = Dst - (0.02 \text{ v } n^{1/2} - 20 \text{ nT})$$

where v is the solar wind speed in km/s, n is the number density in particles per cc and 20 nT is a correction factor related to the effect of magnetopause currents for average solar wind conditions. The Dst data we shall present will be corrected in the above fashion.

In dealing with the perturbation dZ in the Z-component (which is the disturbed field value less the quiet time field value) there are three major concerns:

1. Finding a quiet time field value is not always very easy. It is possible to define a quiet day through use of indices such as Kp, however, even the quietest days defined in this fashion often feature some perturbations. Values of dZ calculated under such conditions will be slightly in error.

2. Subsurface induction effects due to anomalous conductivity distributions can sometimes lead to erroneous results.

3. The ring current actually contributes to the Z-component of the perturbation magnetic field at all latitudes except at the equator.

While there is little that can be done regarding the first two sources of error listed above, it is possible to correct the values of dZ for ring current contributions. To do this, one first corrects Dst for earth induction effects using the technique of *Kisabeth* [1972] to find the perturbation due to the source ring current system. One then finds the component of this perturbation field normal to the earth's surface at the latitude of the observing site. This vertical component is then corrected for induction effects to produce the term which must be added or subtracted from the observed Z-component perturbation to remove the ring current effect. The correction actually involves adding the ring current contribution to the (positive) Z-component perturbations in the afternoon hemisphere due

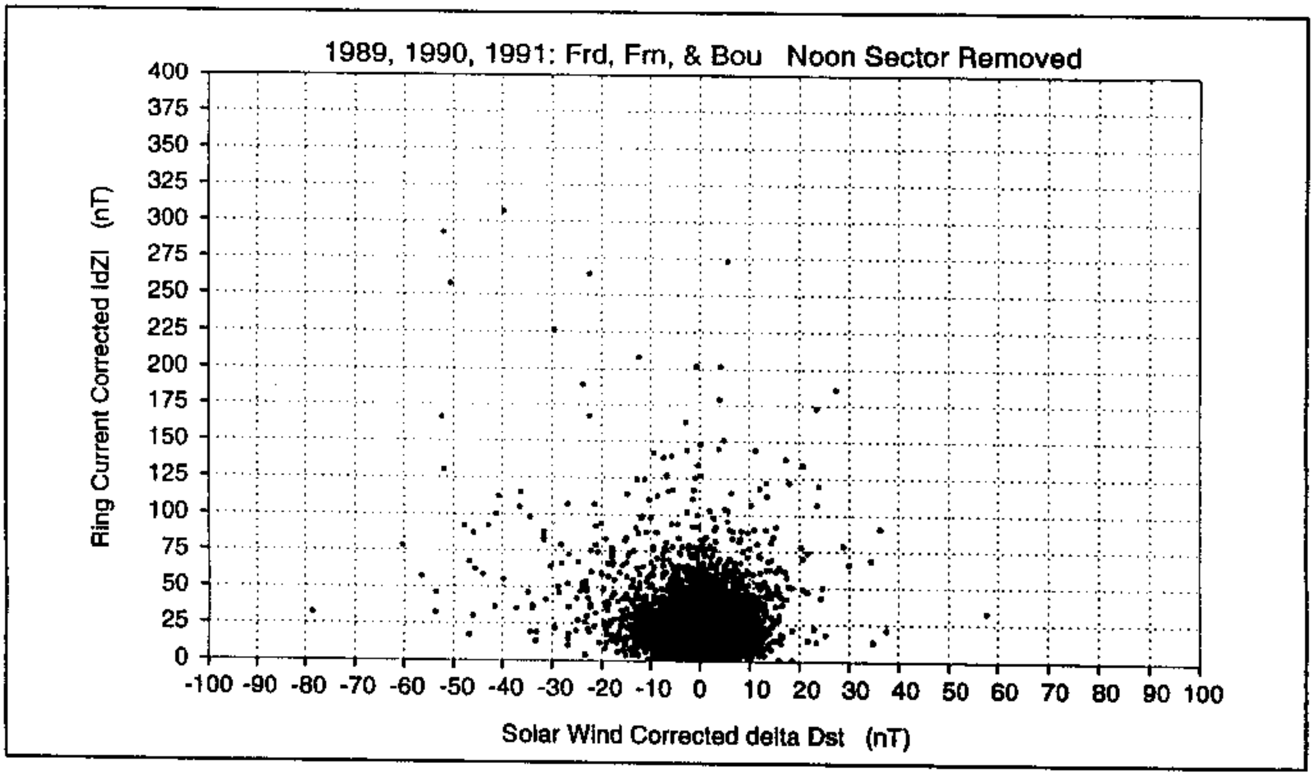

Fig. 4. Plot of the change in Dst from one hour to the next shown as a function of the dZ perturbation due to the edge effects of the auroral electrojets. Each point represents the maximum dZ perturbation at one of the three middle latitude stations of Fredericksburg, Boulder and Fresno for the hour in which the change in Dst would be taking place. The data shown are for the years 1989-1991 inclusive. No data from two hours on either side of local noon at Boulder are considered, as the electrojets in the noon sector are extremely weak in that local time interval and the absence of a significant disturbance dZ would not necessarily rule out the presence of the auroral electrojets at low latitude at other local times.

to the eastward electrojet while subtracting the ring current contribution from the (negative) Z-component in the morning hemisphere.

Figure 4 shows a plot of the change in Dst (dDst) from one hour to the next as a function of dZ in the hourly interval in which the Dst is in process of reaching its new value. Although there is a considerable amount of scatter in the points, there is clearly a trend for larger changes in Dst (i.e. changes making Dst more negative) to be associated with larger values of dZ suggesting that the auroral electrojets move to lower latitudes during periods of Dst growth. This pattern is more apparent when the data are averaged in 10 nT bins for dZ as shown in Figure 5; the data points here reflect cases where there are at least 10 data points in each bin. An interesting facet of Figure 5 is the association of positive increases in Dst with increased dZ. This is attributed to the effect of large substorm expansive phases affecting a significant longitudinal extent, so that the positive H-component within the longitudinal confines of the wedge actually contributes to Dst due to the inability of the small number of Dst stations to adequately identify the asymmetry in the disturbance field. Finally, in Figure 6 we present a set of contour plots reflecting the changes in Dst and dZ for values of |Dst| changes less than 10 nT. One would expect that a zero change in Dst would be associated with very small values of dZ. Clearly such is not the case, and this figure illustrates the sizes of errors one should anticipate in defining the magnitudes of changes in ground disturbance fields at low latitudes due to difficulties in treatment of the data discussed earlier in this section. From Figure 6, it is clear that one should not assign much meaning to changes in Dst of ~5nT or less or to changes in middle latitude ground magnetic perturbations of ~10 nT or less.

From the data shown in this section, we conclude that growth in Dst is indeed associated with equatorward motion of the directly driven auroral electrojets, and hence with the earthward motion of the inner edge of the crosstail current sheet. However, this does not yet answer the question of whether or not substorm expansive phases play a significant role in the energization of ring current particles. Our results thus far suggest merely that ring current particles will be energized only if the inner edge of the crosstail current sheet (as

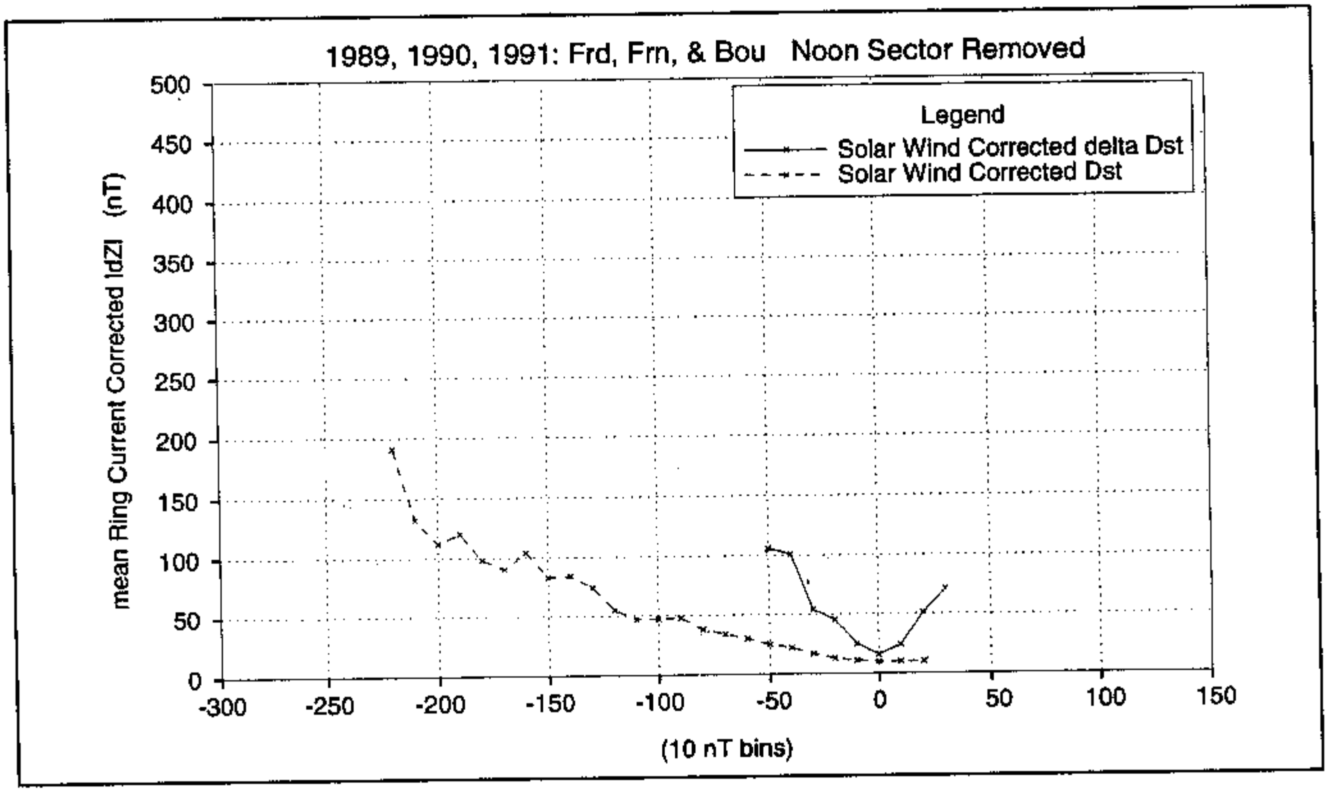

Fig. 5. The same data as shown in Figure 4 except averaged in 10 nT bins for dZ. Clearly the change in Dst from hour to hour (solid line) correlates with Z-component perturbation increases which can be attributed to the proximity of the auroral electrojets. An interesting feature is that positive changes in Dst also seem to be correlated with dZ. Also shown is the average value of Dst in the hour for which dZ is evaluated (dashed line); again the data suggest that increased ring current is associated with auroral electrojet expansion to low latitude.

identified by the proxy measurements of the locale of the equatorward border of the auroral electrojets) moves sufficiently close to the Earth. In terms of the expansive phase itself playing an important energization role, one would have the expectation that a large expansive phase occurring when the auroral oval has expanded far equatorward will have a visible impact on Dst. Figure 7 shows an example of an interval of time in which a ring current has clearly become established and large scale expansive phase activity is in progress. The key event in this sequence occurs in the hourly interval 0600-0800 UT, in which one sees a strong expansive phase onset at ~0620 UT. The large dZ perturbation associated with this onset attests to the fact that the auroral electrojets have moved far equatorward during the course of the main phase development. The value of Dst does not become more negative over the interval 0600-0800 UT suggesting that this strong expansive phase had little effect on ring current strength. One might argue that a large substorm expansive phase might feature a positive H-component disturbance large enough to balance or overpower the negative H-component disturbance expected from an enhanced ring current. However, in this case such an argument does not succeed because it is clear that, in the hour following the expansive phase (0700-0800 UT), Dst still did not become more negative. Since one expects the ring current lifetime to be significantly larger than that of substorm related currents, the fact that Dst did not become more negative in the hour following the expansive phase strongly suggests that the expansive phase occurring in the interval 0600-0700 UT did not cause a ring current enhancement as measured by Dst. This case is very suggestive that individual expansive phases do not have a significant impact on Dst regardless of how far earthward the inner edge of the crosstail current sheet has penetrated. A similar conclusion to this has been reached recently by Iyemori and Rao [1996], although they did not investigate the possible dependence on the latitude at which expansive phases are initiated. Based on the observations described above, we now outline what we believe to be the physics of storm time ring current development.

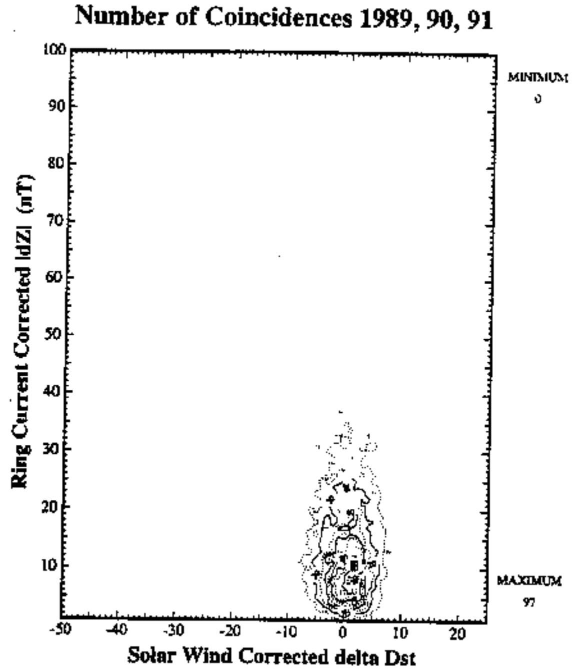

Fig. 6. Contour plots showing the level of uncertainty in correlations between changes in Dst and dZ. This figure suggests that hour to hour changes in Dst which are less than ~5 nT should not be considered as being significant, the same being true for changes in dZ of less than ~10 nT.

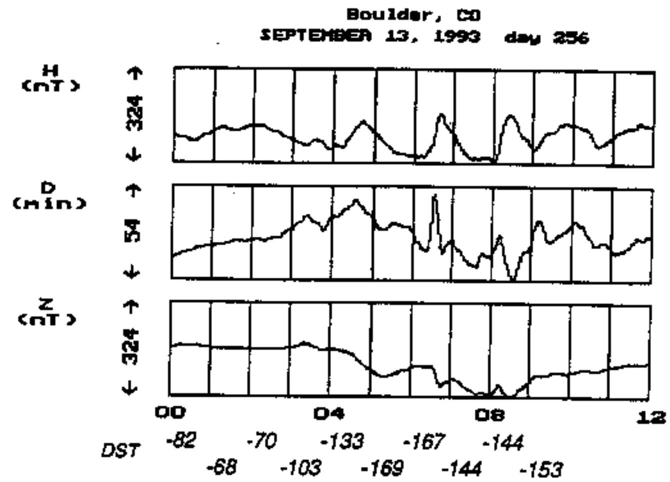

Fig. 7. Magnetogram from the middle latitude station of Boulder showing a period during which the Dst index increased to >-150 nT. The large expansive phase with onset at ~0620 UT does not appear to have any influence in terms of further expansive phase growth despite the fact that the Z-component indicates that the electrojets are displaced rather far equatorward.

4. THE PHYSICS OF RING CURRENT DEVELOPMENT

We couch our description of how substorms affect ring current development in the framework of the boundary layer dynamics (BLD) model of substorms as recently presented by *Rostoker* [1994b, 1996b]. Here we shall concentrate on what happens relatively close to the Earth and not on the high latitude substorm perturbations which likely have little influence on ring current formation. Figure 8 shows the space charge distribution associated with the magnetosphere based on the assumptions of MHD in which space charge density can be expressed by

$$\rho = \varepsilon_0 \operatorname{div} \mathbf{E} = -\varepsilon_0 \mathbf{B} \cdot \operatorname{curl} \mathbf{v} + (1/c^2)\, \mathbf{v} \cdot \mathbf{J}_\perp \qquad (1)$$

where v is the convection velocity and $\mathbf{J}_\perp$ is the component of current flow transverse to the magnetic field with **E** and **B** being the electric and magnetic fields respectively. The first term on the right hand side of Eq. (1) can be associated with vorticity in plasma flow while the right hand term is non-zero when there is a component of transverse current flow in the direction parallel or anti-parallel to the direction of the convective flow of plasma. The space charge associated with the second term on the right hand side of Eq. (1) reflects the shielding of the inner magnetosphere from the primary convection electric field imposed across the plasma sheet through the interaction of the solar wind with the magnetospheric boundary layers. We argue that the conditions for ring current growth begin with the enhancement of the primary convection electric field due to an increase in energy input from the solar wind to the magnetosphere. This increase in energy input could be thought of as being subdivided into two components. Part of the energy is deposited in the ionosphere through directly driven activity while the balance (less any energy deposited back into the solar wind) is stored in the magnetotail. That storage itself can be broken into three components. Part of the energy is stored in the tail magnetic field and the growth of this stored energy is consistent with the strengthening of the crosstail current in the plasma sheet. (This is equivalent to storage of magnetic field in an inductor.) A further portion of the stored energy is found in the convective motion of the plasma as it drifts earthward. (This is equivalent to the storage of electric energy in a capacitor.) The balance of the energy is stored in the gyrational, bouncing and gradient/curvature drift motion of particles acquired through Fermi and betatron acceleration of particles as they drift into the increasingly stronger and more dipolar magnetic field geometry during the development of the substorm growth phase.

The substorm expansive phase reflects a process in which the energy stored in the magnetic field and convective drift motion is converted into gyrational, bouncing and drift motion. Some of the particles so energized precipitate with the energy being lost to the upper atmosphere as heat. Others of the particles are trapped in stable drift orbits around the Earth, and these particles reflect storage of energy as kinetic

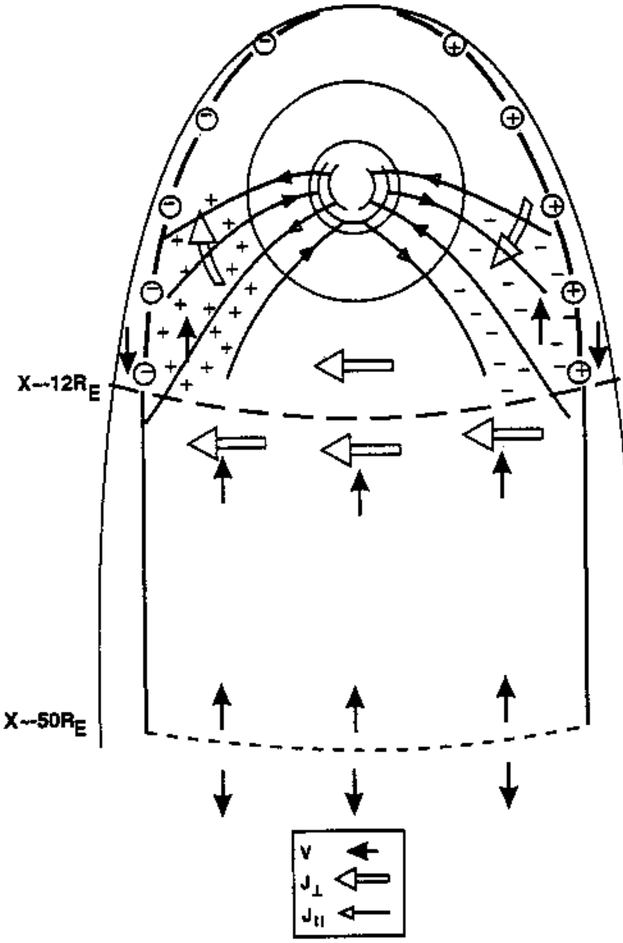

Fig. 8. Cartoon showing the projection of the magnetospheric space charge distribution, convective drift velocity and transverse component of magnetospheric current flow together with the Birkeland current flow shown in perspective (modified after Rostoker, 1994b). The space charge away from the flanks of the magnetosphere near the inner edge of the plasma sheet produces the shielding electric field. Substorm expansive phases are associated with sudden reductions in this shielding electric field which permit magnetotail plasma to penetrate closer to the Earth.

energy of motion and as magnetic energy associated with the flow of current associated with the particle motions. The current we speak of here is the ring current and the stored magnetic energy involves a magnetic field which identifies the ring current and which is represented by the Dst index.

One is then motivated to ask how much energy is available for the energization of particles in the substorm process and in what way this energy is transferred to those particles. If one examines the primary convection electric field, one might conclude that the maximum energy the particles might acquire is that associated with the crosstail electric field. This particular amount of energy would correlate well with the dawn-to-dusk component of the interplanetary electric field (viz., v B_z). Since the crosstail electric field can reach strengths in excess of ~100 keV during magnetospheric storm activity, a considerable portion of the energy of ring current particles should be attributable simply to energization by the convection electric field. This would explain the excellent correlation between ring current intensity (as quantified by Dst) and the dawn-to-dusk component of the interplanetary electric field reported by *Burton et al.* [1975].

However, there are other sources of energy which must be reckoned with. One such source is that associated with large amplitude waves. This concept is inherent in the thermal catastrophe model of *Goertz and Smith* [1989]. It may also explain the non-adiabatic acceleration events in the plasma sheet identified by *Huang et al.* [1992] at times of substorm expansive phase onset. Another possible source lies in heating of plasma sheet particles through reconfiguration of the near-Earth tail magnetic field. *Liu and Rostoker* [1995] have presented a magnetic pumping model for energization of plasma sheet particles through cyclical stretching (viz., growth phase) and collapsing (viz., dipolarization in an expansive phase) of magnetic field lines in the near-Earth plasma sheet. Figure 9 shows the changes in field geometry associated with the Liu and Rostoker proposal. The idea is that as the tail field stretches, ions with zero (90°) pitch angle are scattered to 90° (zero) pitch angles and when the magnetic field dipolarizes, these ions experience some energization. The energization is a second order process, and the ion distribution functions acquire the distinctive characteristics of a Kappa distribution of the type identified by *Christon et al.* [1988] in the near-Earth plasma sheet. We believe that such processes are capable of imparting energies of up to a few tens of keV to plasma sheet particles, bringing them up to sufficiently high "seed" energies that the primary convection electric field, during storm time is able to provide sufficient additional energy to make the ions capable of generating a significant ring current magnetic field.

Based on the above discussion, we consider the development of the ring current to proceed as follows. The enhancement in the primary convection electric field leads to the adiabatic energization of plasma sheet ions (cf. Hines, 1963) as they drift earthward. Near the inner edge of the plasma sheet, the crosstail current can become significantly enhanced [*Kauffman*, 1987] allowing the second term on the right hand side of Eq. (1) to become significant. This term represents the space charge associated with the shielding electric field and a buildup of this shielding charge prevents plasma from convecting closer to the Earth. If the plasma could not convect closer to earth, this would limit the energies to which it could be accelerated and hence restrict the ability of the ring current to grow. To counter this potential difficulty, the substorm expansive phase plays a very important role. As suggested by *Rostoker* [1994b], the fact that the substorm expansive phase involves the sudden reduction of the crosstail current near the inner edge of the plasma sheet is consistent with a sudden decrease in the space charge due to the second term in Eq. (1).

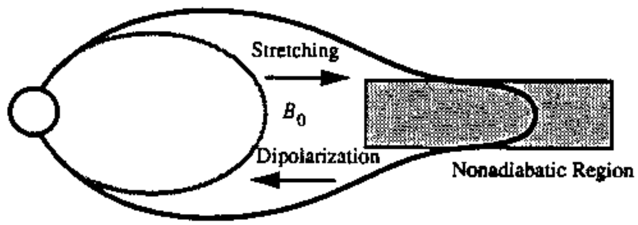

Fig. 9. Changes in field line form associated with the magnetic pumping concept proposed by W. W. Liu and G. Rostoker to energize near-Earth plasma sheet ions (after Liu and Rostoker, 1995). The cyclical stretching and dipolarization of the magnetic field together with pitch angle scattering of the ions leads the significant energization which provides a hot seed population for ultimate ring current growth.

The reduction of this space charge is equivalent to a reduction in the shielding electric field which permits plasma to convect further earthward under the influence of the primary convection electric field. A series of expansive phases under conditions of strong southward IMF for an extended period of time would permit a sequence of buildups and reductions in the space charge associated with shielding, each episode involving processes occurring closer and closer to the Earth. The currents involved in the reduction of shielding charge are, in fact, the Region 2 field-aligned currents. These currents thread the equatorward portion of the auroral oval and hence the earthward movement of the shielding currents would be reflected in the equatorward motion of the equatorward edge of the directly driven auroral electrojets.

We conclude by noting that a sequence of substorm expansive phases such as discussed above, would lead to rapid rises and falls in the electric field experienced by particles in the near-Earth plasma sheet. This type of variable electric field is characteristic of the conditions specified by *Chen et al.* [1993] for effective development of a storm time ring current.

5. DISCUSSION AND CONCLUSIONS

In this paper we have tried to outline the circumstances under which a storm time ring current develops and to acquire some physical insight as to how substorm expansive phases influence ring current growth. Based on our arguments presented above, we conclude that:

1. Ring current particles are energized primarily through the action of the convection electric field as the particles drift closer to the Earth.

2. A non-trivial amount of energy is acquired by the particles through acceleration due to stretching and subsequent dipolarization of the near-Earth tail magnetic field. The action of magnetic pumping is one means by which the particles acquire this energy. When one looks at ring current particles with energies around 150 keV or thereabouts, one should view only a very few tens of keV as being the consequence of dipolarization with the majority of the energy being attributable to the action of the convection electric field.

3. The primary role of the substorm expansive phases during storm main phase development is to break down the shielding electric field making it possible for particles near the inner edge of the plasma sheet to move further earthward and hence to be further energized through adiabatic processes.

It is worth pointing out at this point that the shielding effect that we have been discussing in this paper is unrelated to the shielding associated with the hot particle population responsible for the ring current (cf. Southwood, 1977). The transverse magnetospheric current in that case circles the Earth and thus the current carriers spend a significant portion of their lifetime on field lines threading the high conductivity dayside ionosphere. In our case, the Kaufmann current closes primarily on the near-Earth magnetopause, which results in shielding that differs significantly from that associated with the ring current in that the effect manifests itself outside the ring current regime and the breakdown of this shielding ultimately leads to ring current creation closer to the Earth. This, by no means, suggests that some shielding is not effected by the physical processes described by *Vasyliunas* [1972], *Jaggi and Wolf* [1973], and *Southwood* [1977]. We simply identify another source of shielding associated with the growth of the Kaufmann current and we suggest that the growth and breakdown of this component of shielding plays a key role in the substorm and storm processes.

While one may no longer point to substorm expansive phases as being a primary accelerator of ring current particles, the energy acquired through a sequence of growth and expansive phase cycles may turn out to be of some importance. Figure 10 shows the lifetimes of ring current particles calculated by *Smith et al.* [1981] for a plasma made up of H^+, He^+, He^{++} and O^+ with energies from 10-100 keV. This calculation, relevant for distances from the Earth corresponding to L=5, shows that the lifetime of H^+ depends very strongly on energy. For energies lower than ~40 keV, O^+ has a lifetime greater than that of H+. However, as the energy of the particles increases, the lifetime of the H^+ in the ring current increases significantly. From this diagram, it can be seen that a very few tens of keV can make an enormous difference in the lifetime of the ring current carried by those particles. For this reason, while it is clear that most of the energization of ring current particles is effected by the primary convection electric field, just how large the main phase ring current becomes and how long it persists after the end of the main phase growth may depend significantly on how much energy can be acquired by the ions through acceleration processes such as magnetic pumping.

We should note, in conclusion, that our discussion of substorms in this paper has not involved a treatment of the role of the substorm current wedge (cf. Baumjohann, 1983). The currents that flow as a consequence of reductions of the shielding space charge can be understood in the context of the directly driven system. (In fact, the resultant current flow is into the ionosphere in the evening sector and out of the iono-

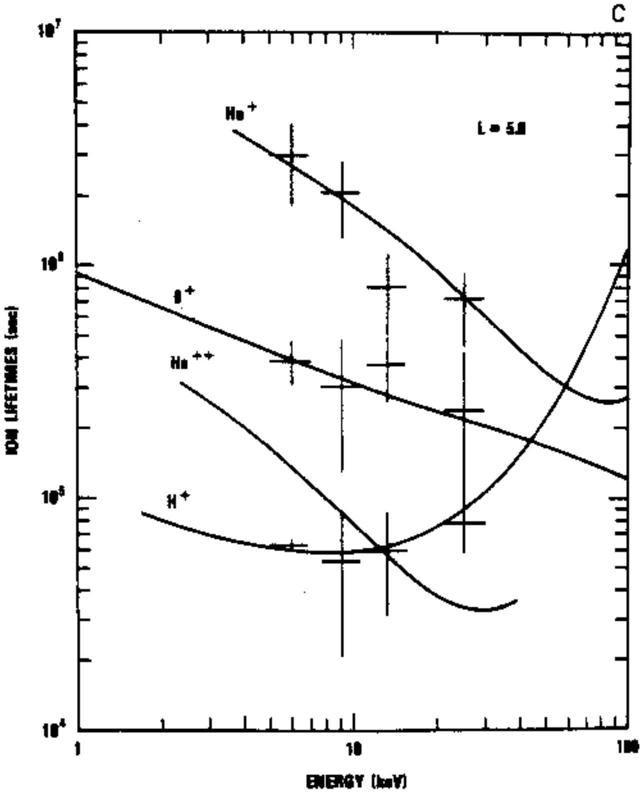

Fig. 10. Lifetimes of ring current ions as a function of their energy for a radial distance from the Earth of L=5 Re (after Smith et al., 1981). Note the steep increase in lifetime of hydrogen ions for energies approaching 100 keV. Clearly the longevity of the ring current is very sensitive to the energization achieved during the development of the storm main phase.

sphere in the morning sector characteristic of the Region 2 currents which are part of directly driven activity.) At this time we do not know if the substorm wedge currents reflect diversion of near-Earth crosstail current into the ionosphere (e.g. Lui, 1996) or whether the mechanism producing the field-aligned currents and associated westward ionospheric electrojet is located further back in the tail. In any event, the impact of the wedge field-aligned currents closer to the Earth is likely to be small when one considers ring current particle acceleration processes so we have chosen not to address the question of the origin of the substorm current wedge in this paper.

Acknowledgements. This research was supported by the Natural Sciences and Engineering Research Council of Canada through a grant to G.R.

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